Experiment-1: Capacitance voltage (CV) chareteristics of PN juntion

The aim of this experiment is to explore the voltage *vs* capacitance plot of a PN Junction diode with varying reverse bias voltage.

Theory:

When p-Si and n-Si come close together fermi level tends to align. This results in the built-in potential, potential across the depletion region in thermal equilibrium, which is given by

$$\phi_i = \frac{kT}{e} \ln \frac{N_A N_D}{n_i^2}$$

A pn junction under reverse bias has a wider depletion region. Reverse bias voltage applied across a p-n diode widens the depletion region. The depletion region width is given by,

$$w = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(\phi_i - V_a)}$$

Reverse bias is associated with a very small current until breakdown takes place. There is also a small capacitance, which must be added to the circuit model of a p-n diode. Capacitance associated with the charges in the depletion layer is called the junction capacitance, while the capacitance associated with the excess carriers in the quasi-neutral region is called the diffusion capacitance. Junction capacitance dominates for reverse-biased diodes, while the diffusion capacitance dominates in strongly forward-biased diodes. The total capacitance is the sum of both. Expressions for the capacitances are obtained by calculating the change in charge for a change in applied voltage, i.e.

$$\frac{d\mathcal{E}}{dx} = \frac{\rho}{\epsilon} \cong \frac{q}{\epsilon_s}(N_D^+ - N_A^-), \qquad for - x_p \leq x \leq x_n$$

A capacitance versus voltage measurement can be used to obtain the built-in potential and the doping density of a one-sided p-n diode. Plotting one over the capacitance squared one expects a linear dependence as expressed by:

$$\frac{1}{C_j^2} = \frac{2}{q\epsilon_s}\frac{N_A + N_D}{N_A N_D}(\phi_i - V_a)$$

The built-in potential is obtained at the intersection of the $1/C^2$ curve and the horizontal axis, while the doping density is obtained from the slope of the curve. A capacitance-voltage measurement also provides the doping density profile of one-sided p-n diodes. For a p^+-n diode one obtains the doping density from:

$$N_D = -\frac{2}{q\epsilon_s}\frac{1}{d\left(1/C_j^2\right)/dV_a}, if\ N_A \gg N_D$$

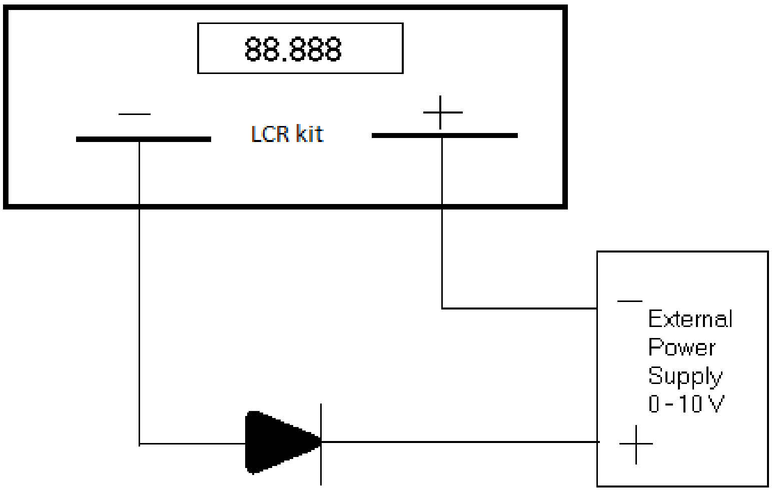
Part-A: Experimental measurement

Components Required:

Diode 1N4007 *(read datasheet)*
Breadboard,

Variable Power Supply of 0-10 v DC,
LCR Kit

Circuit Diagram:



Procedure

1. Make sure the power is off before you build anything.
2. Plug the element (diode) into the breadboard as per circuit diagram.
3. Connect variable voltage source, LCR kit and the diode as shown in circuit on the breadboard.
4. Before making the switch on adjust the knobs of the variable power supply so that the applied voltage at the present position will be zero.
5. Switch on the power supply.
6. Increase the voltage step by step (say **0.1 V**) gradually, note down the capacitance values as per the LCR display and Draw the C-V characteristics graph i.e. Capacitance (pF) versus Voltage (Volts).
7. Plot second graph of $1/C^2$ versus voltage.
8. Estimate built-in potential and doping density.

Part-B: TCAD Simulation

Copy **Sample Code** given below and save it as **pnj.in** (Note: please change **highlighted** parameters only)

```
go atlas
# Define the mesh (Note statements starting with # are comments)
mesh space.mult=1.0

x.mesh loc=0.0 spac=1
x.mesh loc=1.0 spac=1
```

```
y.mesh loc=0.0 spac=1
y.mesh loc=2 spac=0.1
y.mesh loc=4 spac=0.001
y.mesh loc=6 spac=0.1
y.mesh loc=10.0 spac=1
```

Define the region

```
REGION num=1 silicon
```

Define the contacts

```
ELECTRODE NAME=cathode x.min=0.0 x.max=1.0 y.min=0.0 y.max=0.0
ELECTRODE NAME=anode x.min=0.0 x.max=1.0 y.min=10.0 y.max=10.0
```

Define doping for P and N region

```
DOPING UNIFORM CONCENTRATION=1e16 N.TYPE x.min=0 x.max=1 y.min=4.0 y.max=10.0
DOPING UNIFORM CONCENTRATION=3e17 P.TYPE x.min=0 x.max=1 y.min=0.0 y.max=4.0

method newton

solve init
solve Vcathode=-10 outf=pn_cv.str
```

define logfile and Solve statement with AC

```
log outf=pn_cv.log
SOLVE Vcathode=-10 Vfinal=0 Vstep=0.5 NAME=cathode AC freq=1e3
log off
tonyplot pn_cv.log
```

optional extract statements

```
extract name="cv1" curve(v."cathode", c."cathode""anode") outf="cv1.dat"
extract name="cv2" curve(v."cathode", 1/(c."cathode""anode")^2) outf="cv2.dat"
extract name="vbi" xintercept(maxslope(curve(v."cathode", 1/(c."cathode""anode")^2)))
datafile="output.dat"
extract name="dcdv" grad from curve(v."cathode", 1/(c."cathode""anode")^2) where
x.val=-1 datafile="output.dat"
extract name="nd" 1e18*(-2/(1.6e-19*11.68*8.85e-12))/grad from curve(v."cathode",
1/(c."cathode""anode")^2) where x.val=-1 datafile="output.dat"


tonyplot cv1.dat cv2.dat -set pn_cv.set
quit
```

9. Read the output.dat file
10. Obtain C-V data for three cases. (1) $N_A=N_D=3e17$, (2) $N_A=3e19$, $N_D=3e17$ and (3) $N_A=3e17$, $N_D=3e19$.
11. Verify your simulation by extracting doping density and built-in potential from simulated C-V data.
12. Discuss any source of difference between defined and extracted data. Also include the units of the data in discussion.

Experiment-2: Breakdown chareteristics of PN juntion

The aim of this experiment is to study the I-V curve and Breakdown characteristic of the pn junction diode.

Theory:

When p-Si and n-Si come close together fermi level tends to align. This results in the built-in potential, potential across the depletion region in thermal equilibrium, which is given by

$$\phi_i = \frac{kT}{e} \ln \frac{N_A N_D}{n_i^2}$$

A pn junction under reverse bias has a wider depletion region. Reverse bias voltage applied across a p-n diode widens the depletion region. The depletion region width is given by,

$$w = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(\phi_i - V_a)}$$

The maximum reverse bias voltage that can be applied to a p-n diode is limited by breakdown. Breakdown is characterized by the rapid increase of the current under reverse bias. The corresponding applied voltage is referred to as the breakdown voltage.

Two mechanisms can cause breakdown, namely avalanche multiplication and quantum mechanical tunneling of carriers through the bandgap. Neither of the two breakdown mechanisms is destructive. However heating caused by the large breakdown current and high breakdown voltage causes the diode to be destroyed unless sufficient heat sinking is provided. Breakdown in silicon at room temperature can be predicted using the following empirical expression for the electric field at breakdown.

$$|\mathcal{E}_{br}| = \frac{4 \times 10^5}{1 - \frac{1}{3} log_{10}(N/10^{16})} \; V/cm$$

The maximum electric field appears at metallurgical junction, which is given by

$$\mathcal{E}_{max} = \mathcal{E}(x = 0) = -\frac{qN_A x_p}{\epsilon_s} = -\frac{qN_D x_n}{\epsilon_s} = -\sqrt{\frac{2q}{\epsilon_s}\left(\frac{N_A N_D}{N_A + N_D}\right)(\phi_i - V_a)}$$

Assuming a one-sided abrupt p-n diode, the corresponding breakdown voltage can then be calculated as $|V_{br}| = -\phi_i + \frac{|\mathcal{E}_{br}|^2 \epsilon_s}{2qN}$

The corresponding depletion layer width equals: $w_{br} = \frac{|\mathcal{E}_{br}|\epsilon_s}{qN}$

Avalanche breakdown is caused by impact ionization of electron-hole pairs. Under high electric field, carriers gain kinetic energy and generate additional electron-hole pairs through impact ionization. The ionization constants of electrons and holes, α_n and α_p, are defined as the change of the carrier density with position divided by the carrier density, $\Delta n = \alpha_n n \Delta x$. Assuming that the ionization coefficients of electrons and holes are the same, the multiplication factor M, can be calculated from, $M = 1/\left(1 - \int_{x1}^{x2} \alpha dx\right)$. The integral is taken between x1 and x2, the region within the depletion layer where the electric field is assumed constant and large enough to cause impact ionization. Multiplication factor reaches infinity if the integral equal's one, i.e., for each electron coming to the high field at point x1 one additional electron-hole pair is generated arriving at point x2. This hole drifts in the opposite direction and generates an additional electron-hole pair at the starting point x1. This results in an infinite multiplication factor. The multiplication factor is commonly expressed as a function of the applied voltage and the breakdown voltage using the following empirical relation: $M = \frac{1}{\left(1 - \left|\frac{V_a}{V_{br}}\right|^n\right)}, where\ 2 < n < 6$. Temperature coefficient of avalanche breakdown is positive i.e. breakdown voltage increase with temperature. Moreover magnitude of temperature coefficient increases with increase in breakdown voltage.

Zener breakdown is caused by quantum mechanical tunneling of carriers through the bandgap, usually in highly doped p-n junctions. The analysis is identical to that of tunneling in a metal-semiconductor junction where the barrier height is replaced by the energy bandgap of the material. The tunneling probability equals:

$\Theta = exp\left(-\frac{4}{3}\frac{\sqrt{2m^*}}{q\hbar}\frac{E_g^{3/2}}{\mathcal{E}}\right)$, where the electric field $= E_g/(qL)$.

The tunneling current is obtained from the product of the carrier charge, velocity and carrier density. The velocity equals the Richardson velocity, the velocity with which on average the carriers approach the barrier while the carrier density equals the density of available electrons multiplied with the tunneling probability, yielding: $J_n = qv_R n\Theta$. The tunneling current therefore depends exponentially on the bandgap energy to the 3/2 power. Temperature coefficient of Zener breakdown is negative i.e. breakdown voltage decrease with temperature. However magnitude of temperature coefficient is essentially constant with rated breakdown voltage. When zener diodes fail due to excessive power dissipation, they usually fail shorted rather than open i.e. zero voltage like wire.

At a certain doping level and around 6 V for Si, both mechanisms are present with temperature coefficients that just cancel. It is possible to make Zener diodes with quite small temperature coefficients.

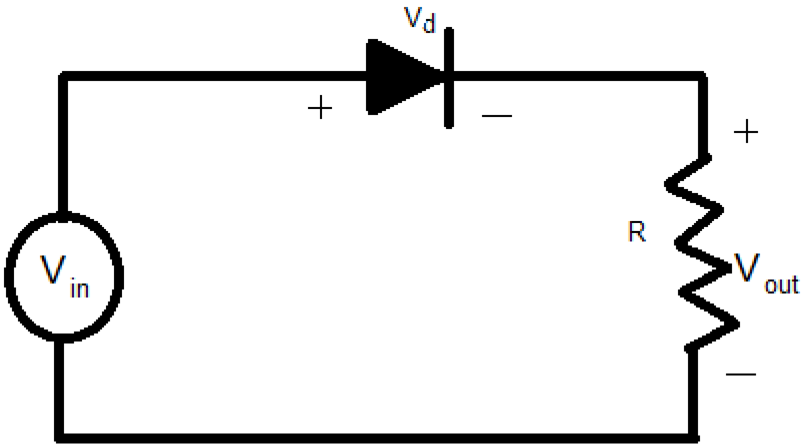
Part-A: Experimental measurement

Components Required:

Diode 1N4007 *(read datasheet)*
Resistors,
Breadboard,
Variable Power Supply of 0-10 v DC,
Multimeter,

Oscilloscope (optional)

Circuit Diagram:



Procedure

1. Read the *datasheet* of the diode. Note down the relevant specifications such as breakdown voltage, built-in potential etc.

2. Use two Multimeters to measure current through the diode and the voltage across the diode. Ensure that diode has the correct polarity: the cathode of 1N4007 is indicated by the black line. Change the diode voltage in the range from 5V to a maximum forward -biased voltage (around 0.7V) that results in the diode current equal to about 10mA. Note that you will need to use different scales for each operating region. In reverse bias, measure in 1 volt intervals. To get the knee of the - diode characteristic in the forward -biased region, choose the voltage steps between "- measurements such that the current change between the steps is not more than about 0.2 mA. When the diode is ON and the diode current is more than about 1 mA, choose the voltage step between measurements such that the current change between steps is about 1 mA. Record the data in a table and include a copy of the data table in the Lab report.

3. Alternatively the diode characteristics can be displayed on the CRO. A time varying voltage source must be used in order to trace both the forward and reverse bias characteristics of the diode. By connecting up the circuit as shown in Figure 1, the diode current (V_R/R) can be found by measuring the voltage across R and the diode voltage can be found by measuring it directly. Thus one of the oscilloscope probes must be placed must be placed across the resistor and the other across the diode.

4. Connect the circuit as shown in Figure (use R = 1kΩ). Use a 5V source with a frequency of 50Hz for the input. In order to protect the diode and the test equipment from over -current, limit the *maximum current through diode to 10mA (typical and diode dependent)*. Change the diode voltage in the range from 0 V to a maximum forward -biased voltage (around 0.7V). Align the voltage waveforms across both the resistor and the diode to the center of oscilloscope screen. Once the alignment has been performed, turn on the X -Y mode. Invert the appropriate channel. The oscilloscope will show you I -V characteristics of the diode. Capture the 1-V

characteristics of the diode to the word document. By sure to scale the vertical axis lin. current (not voltage). Record the data in a table and include a copy of the data table in the Lab report.

5. From the graph of the reverse -bias voltage vs current for diode, Identify the breakdown mechanism and calculate M (multiplication factor) given by $M = I_{OUT} / I_{IN}$ and we know $M = 1/ (1-p)$ where p= probability that carrier have collided. Find M and p.

Part-B: TCAD Simulation

Copy **Sample Code** given below and save it as **pnbd.in** (Note: please change **highlighted** parameters only)

```
go atlas
# Define the mesh (Note statements starting with # are comments)
mesh space.mult=1.0

x.mesh loc=0.0 spac=1
x.mesh loc=1.0 spac=1

y.mesh loc=0.0 spac=1
y.mesh loc=4.0 spac=0.001
y.mesh loc=14.0 spac=1

# Define the region
REGION num=1 silicon x.min=0.0 x.max=1.0 y.min=0.0 y.max=4.0
REGION num=2 silicon x.min=0.0 x.max=1.0 y.min=4.0 y.max=14.0

# Define the contacts
ELECTRODE NAME=cathode x.min=0.0 x.max=1.0 y.min=0.0 y.max=0.0
ELECTRODE NAME=anode x.min=0.0 x.max=1.0 y.min=14.0 y.max=14.0

# Define doping for P and N region
DOPING UNIFORM CONCENTRATION=3e18 N.TYPE REGION=1
DOPING UNIFORM CONCENTRATION=1e17 P.TYPE REGION=2
#save outf=pn_bd.str
material region=1 mun=1450
material region=2 mun=1450

# Inclue recombination/mobility/bg narrowing/energy balance eqn for (e+h)
models srh conmob bgn auger fldmob hcte print

# Impact ionization model with Selberherr relaxation model
impact selb length.rel lrel.ho=0.025 lrel.el=0.025
material taurel.el=0.25e-12 taumob.el=0.25e-12 taurel.ho=0.25e-12
taumob.ho=0.25e-12

# climit set to enhance  accuracy
method block newton climit=1e-5

solve init

# define logfile and Solve statement
log outf=pnbd.log
# compliance limit set on current
```

```
SOLVE Vcathode=0.0 Vfinal=35 Vstep=0.5 NAME=cathode cname=cathode compl=1e-
12
save outf=pnbd.str

contact name=cathode current
method newton climit=1e-5 maxtrap=10
solve imult istep=2 ifinal=1e-3 name=cathode

tonyplot pnbd.log

quit
```

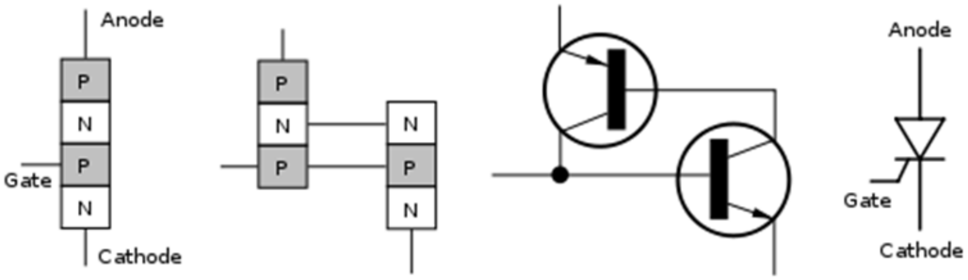
6. Calculate breakdown voltage for pn junction (N_D=3E18, N_A=1E17) from the theory described.
7. Extract the peak electric field profile from pnbd.str and estimate the breakdown voltage. Also include the electric field profile in your report.
8. Compare the two breakdown volages and explain why step-(6) underestimates the breakdown voltage.

Experiment-3: Scr/TRAIC Chareterristics

The aim of this experiment is to obtain the V-I characteristics of SCR and find the break over voltage and holding current

Theory:

A silicon controlled rectifier (SCR) is a semiconductor device that acts as a true electronic switch. It can change the alternating current in to direct current. It can control the amount of power fed to the load. Thus the SCR combines the features of rectifier and a transistor. If the supply voltage is less than the break over voltage, the gate will open (IG = 0). Then increase the supply voltage from zero, a point is reached when the SCR starts conducting. Under this condition, the voltage across the SCR suddenly drop and most of the supply voltage appears across the load resistance RL. If proper gate current is made to flow the SCR can close at much smaller supply voltage.

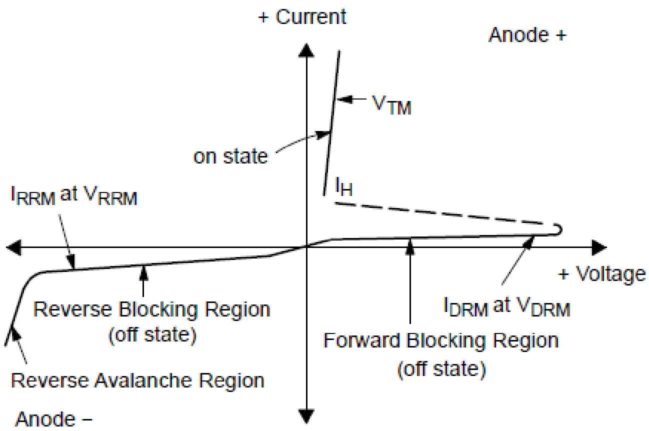


Latching is the required minimum current on the gate that should be used to turn SCR on.

Holding current is the minimum current it can be reduced down to before it opens the path between the cathode and anode.

Voltage Current Characteristic of SCR

Symbol	Parameter
V_{DRM}	Peak Repetitive Off State Forward Voltage
I_{DRM}	Peak Forward Blocking Current
V_{RRM}	Peak Repetitive Off State Reverse Voltage
I_{RRM}	Peak Reverse Blocking Current
V_{TM}	Peak on State Voltage
I_H	Holding Current



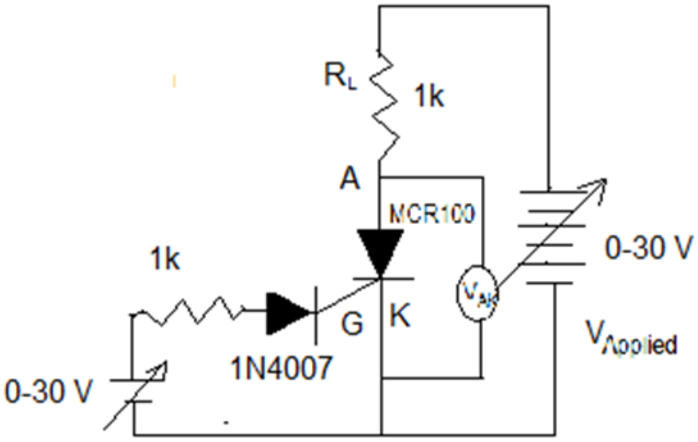
Part-A: Experimental measurement

Components Required:

SCR-MCR100 *(read datasheet)*
Diode 1N4007 *(read datasheet)*

Two 1KΩ Resistors
Breadboard,
Variable Power Supply,
Multimeter

Circuit Diagram:



Procedure

1. Read the *datasheet* of the SCR and diode. Note down the relevant specifications such as breakdown voltage, built-in potential etc.

2. The connections are made as per in the circuit diagram.

3. First by varying Gate voltage then gate current (I_G) is kept constant i.e.20 micro Ampere.

4. The voltage between anode and cathode is increased in step by step (say 0.5v) by varying the V applied.

5. The corresponding anode current (I_A) is noted.

6. After that decrease the applied voltage step by step (say .5v) gradually until the SCR getting off and determine the holding current.

7. The process is repeated for two more constant value of IG i.e. 25 & 30 micro ampere the readings are tabulated.

Result:

I_G = ___________

Applied Voltage	Voltage Across anode and cathode	Current through the load resistance	SCR turn on voltage at gate (VG)

Part-B: TCAD Simulation

Copy **Sample Code** given below and save it as **scr.in** (Note: please change **highlighted** parameters only)

go atlas
Sets variable used to input the doping concentrations for the thyristor layers
SET P1_DOPING=4.0e19
SET N1_DOPING=7.0e15
SET P2_DOPING=2.0e16
SET N2_DOPING=4.0e19

Define the mesh (Note statements starting with # are comments)
MESH SPACE.MULT=1.0
X.MESH LOC=0.0 SPACING=0.1
X.MESH LOC=1.0 SPACING=0.1
Y.MESH LOC=0.0 SPACING=0.1
Y.MESH LOC=0.3 SPACING=0.1
Y.MESH LOC=4 SPACING=0.01
Y.MESH LOC=6 SPACING=0.1
Y.MESH LOC=6.3 SPACING=0.1

REGION NUMBER=1 MATERIAL=SILICON

Defines the Contacts
ELECTRODE NAME=anode TOP X.MIN=0 X.MAX=1
ELECTRODE NAME=cathode BOTTOM X.MIN=0 X.MAX=1
ELECTRODE NAME=gate X.MIN=1 X.MAX=1 Y.MIN=4.5 Y.MAX=5.5

Defines the doping profile of the layers
Doping uniform CONCENTRATION=$N1_DOPING N.TYPE
Doping uniform P.TYPE CONCENTRATION=$P1_DOPING Y.MIN=0 Y.MAX=0.3 X.MIN=0 X.MAX=1
Doping uniform P.TYPE CONCENTRATION=$P2_DOPING Y.MIN=4 Y.MAX=6 X.MIN=0 X.MAX=1
Doping uniform N.TYPE CONCENTRATION=$N2_DOPING Y.MIN=6 Y.MAX=6.3 X.MIN=0 X.MAX=1
Doping uniform P.TYPE CONCENTRATION=$P1_DOPING Y.MIN=4.5 Y.MAX=5.5 X.MIN=0.6 X.MAX=1

#Define models
models conmob fldmob srh auger bgn fermi hcte print
impact selb
contact name=gate current
contact name=anode current

solve init
save outf=scr.str

SOLVE for **Igate = 6.2e-14 to 1e-15 to 1e-17**(converges)
log outf=dummy.log
method newton climit=1e-4 maxtrap=10
solve init
solve ***Igate=5e-14***

log outf=scrg5e-14.log
method newton climit=1e-1 maxtrap=10
SOLVE Ianode=1e-20 Imult Istep=1.5 Ifinal=1e-3 NAME=anode

log outf=dummy.log
method newton climit=1e-1 maxtrap=10
solve init
solve ***Igate=1e-15***

log outf=scrg1e-15.log
method newton climit=1e-1 maxtrap=10
SOLVE Ianode=1e-20 Imult Istep=1.5 Ifinal=1e-3 NAME=anode

tonyplot -overlay -st scrg5e-14.log scrg1e-15.log
quit

8. Identify forward blocking region in the simulated and measured data.

9. Calculate holding current and peak on-state voltage.

10. Why the gate current is taken so low in the simulation?

11. Compare and discuss the experimental data with simulation results